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Development of the Variable Atmosphere Testing Facility for Blow-Down Analysis of the Mars Hopper Prototype

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Abstract. Recent developments at the Center for Space Nuclear Research (CSNR) on a Martian exploration probe have lead to the assembly of a multi-functional variable atmosphere testing facility (VATF). The VATF has been assembled to perform transient blow-down analysis of a radioisotope thermal rocket (RTR) concept that has been proposed for the Mars Hopper; a long-lived, long-ranged mobile platform for the Martian surface. This study discusses the current state of the VATF as well as recent blow-down testing performed on a laboratory-scale prototype of the Mars Hopper. The VATF allows for the simulation of Mars ambient conditions within the pressure vessel as well as to safely perform blow-down tests through the prototype using CO_2 gas; the proposed propellant for the Mars Hopper. Empirical data gathered will lead to a better understanding of CO_2 behavior and will provide validation of simulation models. Additionally, the potential of the VATF to test varying propulsion system designs has been recognized. In addition to being able to simulate varying atmospheres and blow-down gases for the RTR, it can be fitted to perform high temperature hydrogen testing of fuel elements for nuclear thermal propulsion.

Keywords: Mars Hopper, Radioisotope Thermal Rocket, Tungsten Cermet.

INTRODUCTION

Previously, the Center for Space Nuclear Research (CSNR) has proposed a Martian exploration concept that has the potential to extend our current knowledge base of the red planet – the Mars Hopper. This proposed concept is a highly mobile exploration platform comprised of a radioisotope-based propulsion system that allows it to collect samples from one location and then rocket (i.e. hop) up to tens of kilometers away to a new sampling location. With the use of multiple platforms sampling the Martian surface and sub-surface, exploration can be conducted on a global scale – yielding better resource resolution than orbital platforms. Furthermore, a network of hoppers enables a detailed Martian weather monitoring system as well as multi-locational sample collection, making a mars sample return (MSR) mission more attractive.

In development of unique propulsion systems, such as the Mars Hopper, it is important to develop a facility where testing can be conducted on key core components. This effort led to the development of the variable atmosphere testing facility (VATF), where various propulsion systems can be tested with potential gas propellants to determine material-propellant interactions, propellant flow characteristics and internal thermal hydraulics of the core materials. Presented here is a discussion on the development of the VATF to support experimental work conducted on the Mars Hopper laboratory-scale prototype and results of preliminary transient blow-down tests.

MARS HOPPER CONCEPT

The basis of the Mars hopper concept is to utilize decay heat from a radioactive isotope to heat a core material to high temperatures, diverting some thermal power to operate a cryocooler. The cryocooler sublimate freezes the Martian atmosphere (CO_2) at low pressure and subsequently heats it to a liquid state at high pressure, storing it in a separate propellant tank at roughly 2.8 MPa. After the peak design temperature in the core is reached, CO_2 is injected into the core, where thermal energy is transferred to the flowing gas which is expanded through a nozzle, producing thrust. Half of the propellant is consumed through the ascent phase and, after a ballistic coast, the remaining propellant is used for a soft landing. Once landed, samples are collected at the new location and the process repeats.

The Mars Hopper concept's use of radioisotopic decay energy is unique, in that the thermal energy is accumulated in the core overtime. This is important because radioisotope sources have very high specific energy [J/kg], but exhibit rather poor specific power [W/kg]. Therefore, by storing the thermal energy over long periods of time then the power can be dramatically increased over short periods of time; making a radioisotope thermal rocket (RTR) possible. However, to increase the specific power of the RTR, candidate core materials must exhibit high specific heat, high density and high thermal conductivity with a relatively high melting temperature. For the RTR engine of the Mars Hopper beryllium was determined to be the most promising core material due to both its thermal storage capabilities and operational temperature. For example, over the proposed temperature range of 500 K – 1200 K, beryllium has the ability to store 2.01 MJ/kg. This stored energy can then be transferred to a gas flowing through channels fabricated in to the beryllium core. An evaluation of other possible thermal capacitor materials can be found in N.D. Jerred, et al. (2012) and S.D. Howe, et al. (2011).

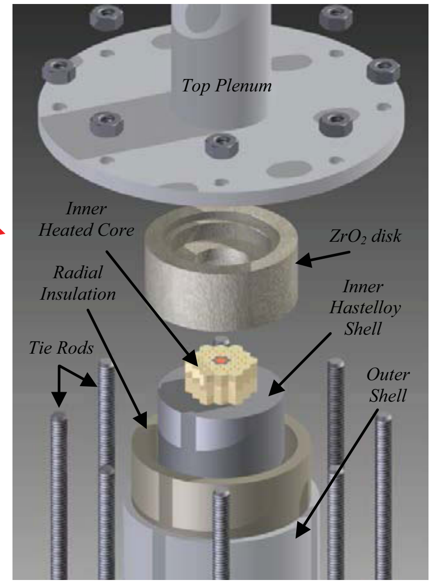
The most optimal radioisotope to provide the needed energy for operation of an RTR is ^{238}Pu, having a long history of use in nuclear batteries. However, to address dwindling ^{238}Pu stocks other radioisotopes have been identified as possible substitutes to supply the needed energy with only minimal core changes needed [Howe, 2011]. To integrate the fuel with the RTR core, a method of encapsulating kernels of fuel (about 100 µm in diameter) within a solid tungsten or tungsten-rhenium matrix is employed. The encapsulating metallic matrix provides high temperature strength and toughness to the surrounding ceramic fuel to prevent fuel dispersion in the case of accidental atmospheric re-entry. Rods of this CERMET (ceramic-metallic) material will then be spaced through the RTR's beryllium core to yield optimal energy input. A more in depth discussion of this encapsulation method is highlighted in R.C. O'Brien, et al. (2008) and R.C. O'Brien, et al. (2009).

The Mars Hopper is designed to utilize the CO_2-rich atmosphere of Mars as propellant, limiting launch mass and increasing the probe's potential mission lifetimes. Two key subsystems work in unison to achieve the task of acquiring the needed propellant – the energy conversion subsystem and the liquefaction subsystem. The energy conversion subsystem being proposed will utilize thermal photovoltaic (TPV) energy conversion. TPV cells will convert thermal energy losses emitted from the core into usable electrical energy. Converted thermal energy will be used to operate a cryocooler at the heart of the liquefaction subsystem. The cryocooler allows for CO_2 to sublimate freeze on to an internal cold finger. The solid CO_2 will then be slightly heated to a liquefied state and stored in an attached propellant tank. Although fractions of a gram of CO_2 can be produced per liquefaction cycle, continuous operation will produce the needed 25 kg of propellant for each hopping maneuver. A more detailed assessment of the Mars Hopper can be found in S.D. Howe, et al. (2011).

Laboratory-Scale Prototype

In the development stages of the Mars Hopper it was important to perform computational fluid dynamic (CFD) analysis of propellant flow and thermal hydraulic studies of the probe to overcome thermal isolation issues and to more accurately predict the actual performance of the hopper. However, due to the non-ideal-gas behavior of CO_2, and to test various insulation schemes, the importance of designing a laboratory-scale test rig of the Mars Hopper was recognized in order to provide benchmark data for comparison to the simulations. With empirical data both CFD and thermal hydraulic codes can be validated, allowing for design iterations to be performed numerically in order to fine tune the probe's design and ultimately maximize its performance.

The test rig design is radially scaled down from the flier version, while the proposed core length has been maintained. For gas management the test rig utilizes two gas plenums for both gas injection and exhaust handling. The entire inner assembly is encased by a titanium shell which contains both the radial insulation scheme and the inner core. At the center of the core is a 275 W electric heater to simulate radioisotope decay heat. To thermally isolate the core axially from the injection and exhaust plenums, cylindrical zirconia disks have been designed. Tie rods connected to flanges fitted to each plenum are used to axially compress the entire test rig through thermal cycling and blow-down testing. Figure 1 shows both a picture and drawing representation of the assembled test rig.

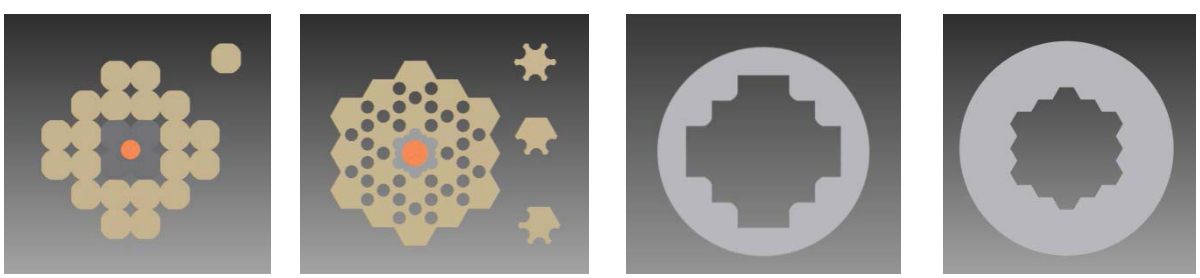


(a) (b)

FIGURE 1. A Representation of the Assembled Prototype where (a) Shows the Actual Assembled Test-Rig and (b) Shows a CAD Blown-Up View of the Top System Assembly.

Consideration of several initial design concepts for the test rig's inner core led to the selection of using an array of bundled rods. This configuration was determined to be best suited from both a fabrication and materials handling perspective. With the thermal capacitor material being hazardous, a metallic coating was applied to the beryllium rods to ease handling and blow-down testing concerns. In order to ensure that the inner surfaces of the flow channels were properly coated through their entire length, the bundled rod core design was found to be the most practical. This design allows for each rod to provide a segment of the flow channel on their outer perimeter. Therefore once the rods are bundled together, a full flow channel pattern is visible. For the metallic coating, a material with a similar coefficient of thermal expansion (CTE) to that of beryllium must be used to prevent flaking through thermal cycling, thus the nickel-based alloy Hastelloy C-276 was chosen.

Two rod designs were pursued, which produce two unique inner core assemblies and flow channel geometries. Figure 2 shows both inner assembly cross-sectional profiles where Fig. 2 (a) is made up of circular-based rods and Fig. 2 (b) of hexagonal-based rods. At the center of the inner assemblies is the heater rod (shown in red), which is encased in a Hastelloy C-276 shell designed to fit in the respective assembly. In order to radially contain the inner bundled rods, a Hastelloy C-276 outer shell is again employed for each respective design as seen in Fig. 2 (c) and (d).



(a) (b) (c) (d)

FIGURE 2. CAD Drawings of the Inner Core Assembly Parts for the Test Rig where (a) Shows the Circular-Based Design, (b) Shows the Hexagonal-Based Design and (c) Shows the Outer Shells for Each Bundled Core Design.

Based off of initial rod designs, as seen in Fig. 2 (a) and (b), beryllium rods have been procured for the project. However, in order to perform testing at the available facilities, a set of rods for each design made of Hastelloy C-276 was fabricated as a surrogate for the beryllium rods. With the beryllium rods stored at the Idaho National Laboratory the current project's work scope included thermal cycling of the prototype to test its structural integrity and to perform preliminary blow-down testing with CO_2 gas to better understand the test rig's performance and finalize its overall design. After these initial tests, final tests will be performed using the beryllium rods. Figure 3 shows a cross-sectional view of the test rig fully assembled, again showing the inner core components and the flow direction.

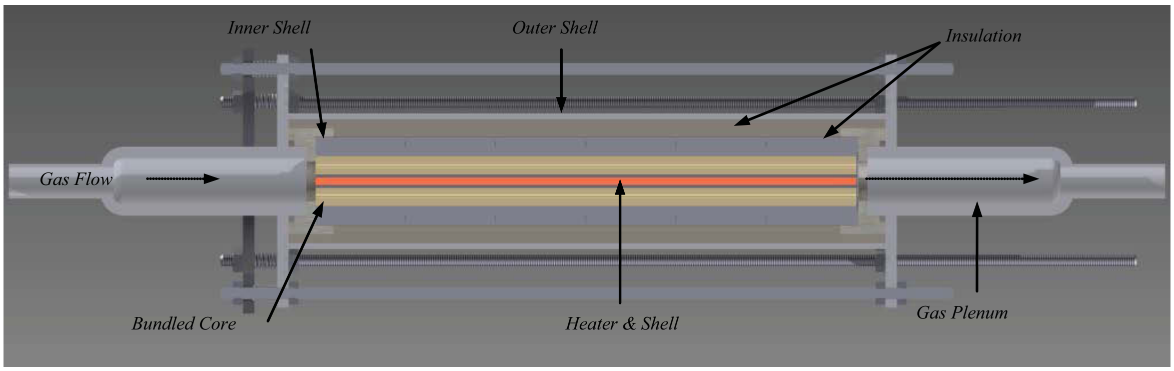


FIGURE 3. CAD Drawing Showing a Cross-Section View of the Fully Assembled Test Rig.

VARIABLE ATMOSPHERE TESTING FACILITY

The VATF was initially commissioned as the hot hydrogen testing facility (HHTF) located at the Idaho National Laboratory. A full description of the HHTF can be found in W.D. Swank, et al. (2007) and is briefly summarized here. The HHTF had the capability of testing various core materials in 2500°C hydrogen flowing up to 1500 liters per minute. At the heart of the HHTF is a vacuum/pressure chamber that is shown in Fig. 4. This chamber is a double walled design to allow continuous water cooling and is certified for operation between 1.33 E^{-4} Pa ($1E^{-6}$ torr) up to 344.74 kPa. To accommodate test components three large ports (36 cm in diameter) allow access to the internal chamber being 45 cm in diameter and 163 cm in length. Located above the main vessel of the chamber is a cylindrical spool with several small access ports (3.8 cm in diameter) to provide feedthroughs for instrumentation and gas injection. The entire chamber is capped with a dome to allow for long test components.

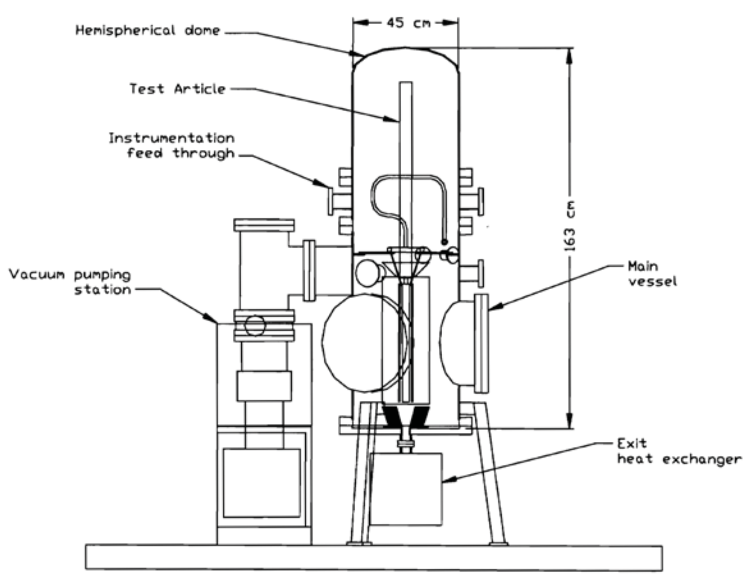


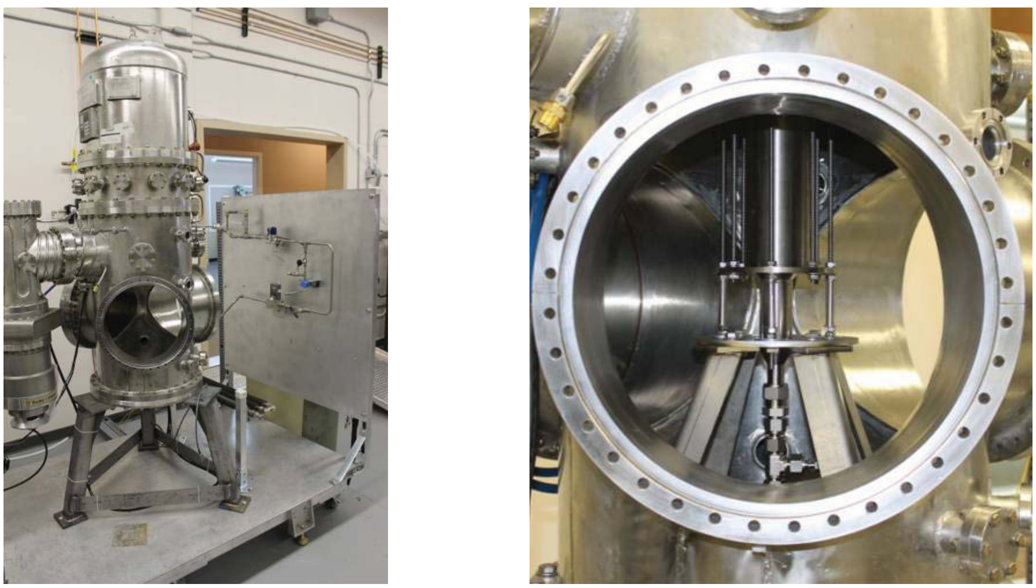
FIGURE 4. Drawing of the HHTF Pressure/Vacuum Vessel Used for the VATF [Swank, 2007].

To evacuate the chamber an attached vacuum system utilizes a two-stage mechanical pump to reach a rough vacuum atmosphere, where high vacuum atmospheres can be reached through the use of the turbo pump connected in series with the mechanical pump capable of 1000 liters/second. For high temperature internal heating radio frequency induction coils provided by high power feedthroughs are capable of providing up to 50 kW of power, while moderate temperatures (< 1000°C) can be reached through the use of insertion heaters [Swank, 2007].

The CSNR was able to procure the equipment and through the previous year's efforts the chamber was refurbished and recertified for its original operational parameters discussed above. The VATF provides multi-functional testing capabilities for various types of core components and flowing gases. Traditionally, it was designed to perform high temperature hydrogen experimentation of single components and now has the capability of testing scaled-down propulsion systems utilizing various flowing gases, surrounding atmospheres and assembly designs.

Mars Hopper Prototype – VATF Integration

The hopper prototype was integrated into the VATF's vacuum chamber, which can be seen pictured through a main access port in Fig. 5 (a) and (b). The vacuum chamber allows for the simulation of Martian ambient conditions such as providing a rough vacuum of 0.01 atm as well as a CO_2 atmosphere. Additionally, the vessel also acts as an engineered safety control, where in the event of a failed blow-down test operators are protected. A pressurized train is integrated with the test rig to safely inject as well as handle the hot CO_2 exhaust gas.



(a) (b)

FIGURE 5. Shows Portions of the Test Facility Where (a) is the Pressure Vessel and (b) is the Test Rig Assembled within the Pressure Vessel.

Upstream of the test rig and connected to the pressurized train is a mass flow meter and variable-area flow valve to control and monitor gas flow rates through the prototype. Hot gas exiting the test rig was passed through a finned heat exchanger where it was cooled prior to flowing into the general laboratory exhaust system. The test rig itself was fitted with various thermocouples in order to monitor the inner core temperature at varying axial positions, to provide a control feedback loop to a PID controller for the heater and to monitor the outer shell temperature throughout each experiment. Gas pressure data was gathered via an upstream pressure transducer, as well as a differential pressure transducer, measuring the pressure drop across the core. Additionally, gas temperatures were measured upstream and downstream of the heated rig. To ensure inner wall temperature limits of the vessel are not exceeded, a thermocouple was attached directly adjacent to the test rig. A complete customized Labview suite was developed to monitor and record all temperature, pressure and gas flow rate data throughout each blow-down test.

Preliminary Test Results

Preliminary transient blown-down tests were performed in the VAFT using the Mars Hopper test rig. For these tests, the inner core assembly was electrically preheated to a maximum temperature of 670°C. At the start of the test, a metered flow of carbon dioxide gas was suddenly initiated, resulting in flow through the core flow channels. The test was ran for a total duration of 10 minutes (600 s) and pertinent data gathered from this test is displayed in Fig. 6. When the solenoid valve in the gas delivery system is opened, the gas flow ramps up from 0 to 147 slpm over the first 100 seconds and is steady thereafter. The center line temperature, initially at 670°C, dropped rapidly to a final value of 147°C. The outer spacer temperature, had an initial value of 615°C, and showing a slower response, cooled to a final value of 316°C at the end of the 600 second transient. The gas exhaust temperature rose rapidly from 48°C to 344°C upon initiation of gas flow. It subsequently cooled slowly to a final value of 258°C at the end of the 600 second transient. This temperature response in the gas exhaust, compared to thermal measurements throughout the core shows thermal energy contained in the core was capable of sustaining gas temperatures exiting the core. Additionally, it should be noted for this experiment a 600 second transient was chosen in order to visualize the temperature and flow characteristics of a blow-down test, for the proposed Mars Hopper a hopping maneuver will consist of two 20 second blow-downs – ascent and descent. Furthermore, these results provide a good *first-cut* analysis of the test rig design, as well as yield valuable validation data for comparison against thermal response predictions from computational models.

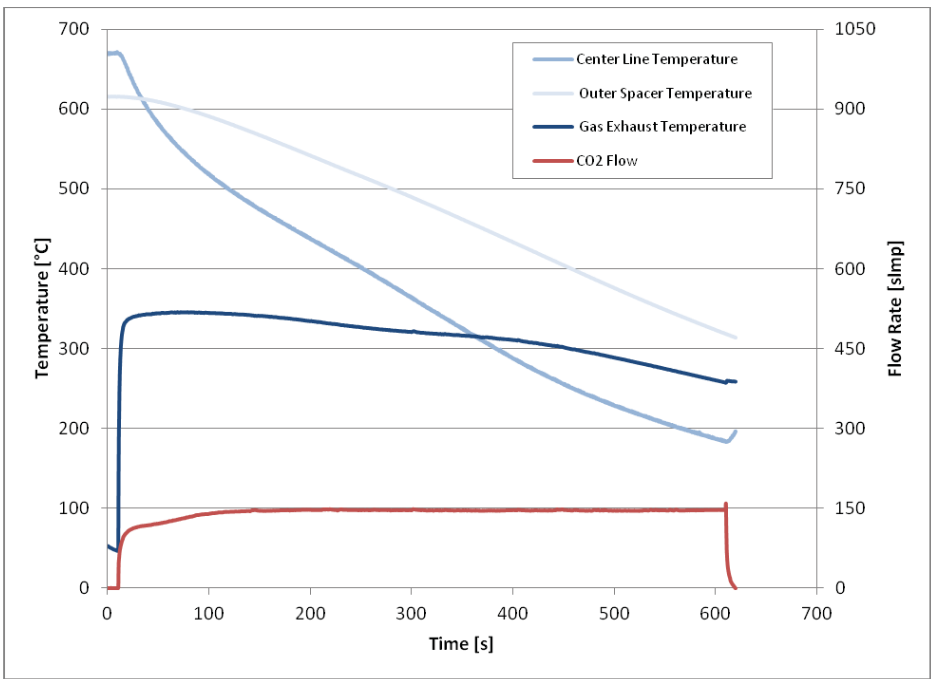


FIGURE 6. Time History of Flow Rate and Core Temperatures During Carbon Dioxide Blow-Down Test.

TECHNOLOGY POTENTIAL

Through the course of the Mars Hopper project, the RTR concept, used to propel the hopper from one location to the next, was recognized to have additional applications beyond the Mars exploration platform. With minimal core changes, the RTR inner core assembly has the potential to serve as an exploration platform for other extra-terrestrial bodies, as an interplanetary propulsion system and as a pulsed power production method for orbital platforms.

One such extra-terrestrial body that has been identified as a possible location for an RTR-based exploration platform deployment is Jupiter's satellite Europa. Europa is thought to be comprised of mostly water, covered with a thick sheet of ice. Under the understanding that life exists at thermal vents located in the depths of Earth's oceans, similar vents may exist on Europa, which may also harbor life. A Europa hopper could be designed to extract water from the surface, which could be used as propellant to allow the platform to explore surface cracks where the underlying liquid water may be exposed to the surface. This mobile platform would resemble the Mars Hopper very closely, except for the propellant extraction subsystem.

A radioisotope-based interplanetary propulsion system has been identified as a very promising platform based on the RTR concept. This propulsion system would be a bimodal design utilizing thermal energy for a high thrust mode and using electrical energy to operate ion thrusters for low thrust. The high thrust mode would be used to escape high gravity wells, e.g. Earth orbit, in a timely manner and would consist of blowing stored propellant through the core and out a nozzle. For interplanetary travel ion thrusters will be used to achieve higher propellant efficiencies, i.e. high Isp. Thermal energy from the core will be converted to electrical energy via TPV energy conversion, which in turn would be used to operate the ion thrusters. This propulsion system is especially attractive for use with CubSat and NanoSat platforms, where small cheap simple satellite packages can be delivered to various interplanetary bodies. To date CubSats have been limited to Earth orbit having only a small solar cell grid for electricity production, using the RTR concept in this fashion enables outer planetary body exploration.

For orbital platforms, either in orbit about Earth or another planetary body, where high power consumption may not be needed; a closed-loop, blow-down system may be designed around the RTR core for pulsed-power production. The system design would likely be based around the thermodynamic Brayton cycle, where a working fluid is heated through the thermal capacitor core, passed over a turbine to produce electricity and then flowed through a heat exchanging system to dissipate excess thermal energy to the environment. Electricity produced could either be stored in batteries for continuous use between blow-downs or blow-downs could occur whenever probe functionality is needed. If extensive time between blow-downs is needed a passive cooling system of the core can be enacted to maintain a certain temperature.

CONCLUSION

With decreasing budgets and the push to perform *cheap* science, the proposed Mars Hopper may be attractive due to its small size and simple design. Extending on the legacy of the current rover program, the use of multiple transient platforms can increase our knowledge base of the Martian planet and yield resource information on a global scale. Furthermore, the RTR concept that is used in the Mars Hopper may prove to be a capable propulsion system for numerous applications and with the Mars Hopper development a test facility (VATF) was assembled capable of testing these unique propulsion system concepts. Since each variation introduces changes in engine functionality and the overall system the VATF will prove to be useful in testing these changes, determining system performance as well as determining the most optimal propellant for each design.

ACKNOWLEDGMENTS

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